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Prediction of soil detachment in agricultural loess catchments: Model development and parameterisation

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ABSTRACT

The objective of this paper is to derive and parameterise a detachment approach that balances simplicity and necessary process complexity to be implemented in a process-based erosion model applicable at the catchment scale. We proposed a semi-empirical model approach that relates the potential detachment rate by means of a bi-linear combination to the attacking forces of rainfall (characterised as momentum flux of rainfall) and overland flow (characterised as shear stress). The resisting forces against detachment are characterised by two empirical parameters: i) erosion resistance f_{crit}, which is a threshold of the attacking forces and ii) erodibility parameter p_1, which represents the linear increase of detachment once the erosion resistance is overcome. The parameter P_2 weights the momentum flux of rainfall against shear stress. The empirical parameters were determined for conventionally tilled loess soils using data sets of rainfall simulation experiments performed in the laboratory and in the field. At first, a data set of laboratory experiments carried out under varying conditions of rainfall and overland flow (published by Schmidt, 1996) but using resembling loess soil samples was used to determine the parameters p_1 and P_2. Secondly, data from 58 rainfall simulation experiments performed on 24 m^2 plots in the Weiherbach catchment (Southwest Germany) were used to parameterise the erosion resistance f_{crit} under field conditions. We found evidence that cultivation was the first order control of the erosion resistance on conventionally tilled loess soils: crops that are cultivated in rows were strongly susceptible to detachment because runoff is channelled along the intermediate areas of plant rows. For bare soils we found a strong correlation between the erosion resistance, surface roughness and clay content. These results can be used to predict the erosion resistance and regionalise it to the catchment scale as input parameter in a soil erosion model.

1. Introduction

Erosion on agricultural land disturbs the ecological functions of the soil and causes damage to adjoining ecosystems, in particular surface waters, which are threatened by the input of sediments and associated nutrients and contaminants (Kronvang et al., 2007; Owens et al., 2008; Scherer et al., 2003). Loess soils are especially highly susceptible to erosion due to their high silt content. In addition they are frequently used for intensive cultivation. Soil particle detachment is a key process affecting water erosion, since it determines the amount of sediment that is potentially transferred to surface water bodies. Detachment of soil particles depends on various factors such as hydro-meteorological forcing, soil hydraulic and mechanical properties, land use (in particular soil cover and type of crop) and tillage practice. As with most other sub processes that determine water erosion, particle detachment is only directly observable at small scales within laboratory and field experiments. Process-based numerical erosion models are thus used for extrapolating the findings from the plot scale to the catchment scale in order to quantify spatially varied erosion and deposition rates as well as sediment yields at the catchment outlet.

Soil particle detachment is triggered by the attacking forces of raindrop impact and overland flow. Detachment induced by rainfall occurs primarily on interrill areas (Kinnell, 2005; Salles et al., 2000) while flow detachment mainly occurs by sheet flow or concentrated overland flow in micro-relief channels (Foster, 1982; Knapen et al., 2007a). Several process based erosion models therefore distinguish between interrill and rill detachment e.g. WEPP (Flanagan et al., 2001), EUROSEM (Morgan et al., 1998), GUEST (Rose et al., 1998) or LISEM (De Roo et al., 1998; Takken et al., 2005). A few models explicitly consider the effect of tillage operations on flow direction, but so far, they were only applied in very small catchments (Fiener et al., 2008; Takken et al., 2001, 2005). All the listed models are based on the essential assumption of a fixed rill geometry. However, the spatial separation of rill and interrill areas is often not clearly defined, does

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vary in time (Giménez and Govers, 2001; Lei et al., 1998; Nearing et al., 1997) or is not known on larger scales. Models that aim at the catchment scale thus often handle detachment by rainfall and overland flow as integral response in an effective lumped manner (Huang and Bradford, 1993; Owoputi and Stolte, 1995) e.g. KINEROS2 (Smith et al., 1995), SHESED (Wicks and Bathurst, 1996), OPUS (Heatwole et al., 1998), LISEM (De Roo et al., 1998), EROSION 2D/3D (Schmidt et al., 1999) or CASC2D-SED (Johnson et al., 2000). This approach implies that the attacking forces of rainfall and overland flow are also treated in a merged manner and are related to observed detachment rates gained within rainfall simulation experiments on erosion plots. Thus, in a first step, the attacking forces of rainfall and overland flow have to be quantified.

Frequently the impact by rainfall is characterised using rainfall intensity or variables such as kinetic energy or momentum flux of rainfall (Foster, 1982; Gao et al., 2003; Liebenow et al., 1990; Meyer and Wischmeier, 1969; Quansah, 1981; Rose et al., 1983; Sharma et al., 1993; Zhang et al., 1998). All proposed variables to determine rainfall impact on the soil matrix depend on drop diameter and fall velocity. This is why Salles et al. (2000) directly relate these basic parameters to rainfall detachment.

The attacking forces of detachment by flow are mainly controlled by slope and overland flow rate (Nearing et al., 1991; Zhang et al., 2003). The most commonly used variables are total shear stress τ or effective shear stress τ_{eff} (Foster, 1982; Foster et al., 1995; Franti et al., 1999; Govindaraju, 1998; Léonard and Richard, 2004; Wicks and Bathurst, 1996), stream power ω (Elliot and Laflen, 1993; Hairsine and Rose, 1992a; Hairsine and Rose, 1992b; Rose et al., 1983; Van Oost et al., 2004), unit stream power P (McIsaac et al., 1992) and unit length shear force Γ (Giménez and Govers, 2008). According to varying experimental set-ups of single studies, different hydraulic variables have been proven as applicable (Elliot and Laflen, 1993; Giménez and Govers, 2002; McIsaac et al., 1992; Nearing et al., 1991; Zhang et al., 2003). This is due to the fact that under single experimental conditions all meaningful hydraulic variables are strongly correlated and therefore varying relationships can be adapted to predict measured soil detachment rates (Govers et al., 2007). Giménez and Govers (2002) examined the correlation of various hydraulic variables and measured flow detachment rates from laboratory experiments with smooth and rough bed geometries. Only unit length shear force Γ and shear stress τ were capable of directly accounting for varying bed geometries. Both variables therefore appear to be more universal to quantify the attacking forces of flow (Giménez and Govers, 2002; Govers et al., 2007).

In the next step, the variables to quantify the attacking forces of rainfall and overland flow have to be related to observed detachment rates. The detachment process is a threshold phenomenon i.e. particle detachment starts when the attacking forces exceed a critical resistance of soil against erosion (Cammeraat, 2004; Foster, 1982; Knapen et al., 2007a; Zehe and Sivapalan, 2009). According to this threshold concept, the beginning of particle detachment can be related to the amount by which the above mentioned variables, characterising the forces of rainfall and overland flow, exceed a critical value. Due to the involvement of friction processes soil detachment is one of the most complex processes within soil erosion modelling. Hence the most detachment models are based on empirical or semi-empirical approaches. However, the necessary empirical parameters such as soil erodibility are difficult to estimate since they are not directly measurable. Furthermore, the more complex the input requirements of a model, the greater the resulting uncertainty with that model may be (Brazier et al., 2000). Due to the uncertainty associated with input parameters, complex models do not necessarily perform better than simpler model approaches (Fiener et al., 2008; Jetten et al., 2003). We therefore suggest that successful modelling of detachment at the catchment scale requires adjustment of the right balance of process detail to avoid over-simplification and model simplicity. Such a balanced model should, thus, represent the main structural elements of the landscape that affect detachment of soil particles within the model parameterisation (Jetten et al., 2003; Zehe and Sivapalan, 2009).

The objective of this study was to derive and parameterise an effective detachment approach that combines the attacking forces of rainfall impact and overland flow to be implemented into a process based erosion model, which is applicable at the catchment scale. To reach this aim we addressed the following tasks: i) introducing a semi-empirical model approach to quantify detachment by rainfall and flow, ii) determining the empirical parameters of the detachment model for conventionally tilled loess soils using data of rainfall simulation experiments carried out in the laboratory (published by Schmidt, 1996) and in the field, iii) explaining the variation of observed detachment rates under field conditions by varying only one empirical parameter, namely the erosion resistance and iv) relating the parameter erosion resistance to characteristics of the erosion plots to predict and regionalise it for simulations at the catchment scale.

2. Material and methods

2.1. A lumped model approach for soil detachment by rainfall and overland flow

The most commonly used relationship to quantify detachment by flow was introduced by Foster (1982) and expresses the detachment rate as being proportional to the excess of shear stress:

$$e_q = K_c \cdot (\tau - \tau_{cr})^b \tag{1}$$

where e_q is detachment rate by flow (kg m^{-2} s^{-1}), τ shear stress (N m^{-2}), τ_{cr} critical flow shear stress (N m^{-2}), K_c dimensioned empirical parameter characterising flow erodibility (s m^{-1}) and b dimensionless empirical exponent.

As outlined by Giménez and Govers (2002) and Govers et al. (2007) shear stress is approved to account for varying bed geometries (Section 1). We therefore consider shear stress as a suitable variable to quantify detachment by flow on cultivated loess soils and extended the detachment model proposed by Foster (1982) (Eq. (1)) to account for rainfall impact, too. Different variables are adequate to quantify the attacking forces of rainfall (Section 1). We choose the momentum flux of rainfall m_r, that was used in the model EROSION 2D/3D (Schmidt et al., 1999; Schröder, 2000). The momentum flux is quantified using water density, fall velocity of raindrops and rainfall intensity as spatially and temporally averaged variables to characterise the momentum of rain drops. Only the component of the momentum flux of rainfall, that is perpendicular to the soil surface provokes particle detachment (Bradford and Foster, 1996). Thus the momentum flux was multiplied with the cosines of slope angle to consider the angle of drop attack (Eq. (2)). The impact of rainfall on the soil matrix is diminished by leaves, stones and plant residues. Therefore only the uncovered parts of the soil surface are considered as susceptible to rainfall detachment (Rose et al., 1983). In Eq. (2) the fall velocity of raindrops is required. Schramm (1994) quantified the fall velocity of raindrops for rainfall intensities ranging from 5 to 100 mm h^{-1} and found a logarithmic relationship between both parameters. He derived an empirical relation to determine mean fall velocity from rainfall intensity (Eq. (3)).

$$m_r = \rho_w \cdot r \cdot \cos\alpha \cdot v_r \cdot (1 - SC) \tag{2}$$

$$v_r = 4.459 + 0.613\,\ln(r \cdot \cos\alpha) \tag{3}$$

where m_r is momentum flux of rainfall (N m^{-2}), ρ_w water density (kg m^{-3}), r rainfall intensity (mm h^{-1}), α slope angle (degree), v_r fall velocity of raindrops (m s^{-1}) and SC soil cover (in percent).